ADAPTIVE CONTROLLER ADAPTATION TIME AND AVAILABLE CONTROL AUTHORITY EFFECTS ON PILOTING

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Adaptive control is considered for highly uncertain, and potentially unpredictable, flight dynamics characteristic of adverse conditions. This experiment looked at how adaptive controller adaptation time to recover nominal aircraft dynamics affects pilots and how pilots want information about available control authority transmitted. Results indicate that an adaptive controller that takes three seconds to adapt helped pilots when looking at lateral and longitudinal errors. The controllability ratings improved with the adaptive controller, again the most for the three seconds adaptation time while workload decreased with the adaptive controller. The effects of the displays showing the percentage amount of available safe flight envelope used in the maneuver were dominated by the adaptation time. With the displays, the altitude error increased, controllability slightly decreased, and mental demand increased. Therefore, the displays did require some of the subjects' resources but these negatives may be outweighed by pilots having more situation awareness of their aircraft.

Adaptive control in flight applications has a long and rich history dating back to the 1950s. Currently, adaptive control is beneficial for highly uncertain, and potentially unpredictable, flight dynamics characteristic of upset recovery or damage induced on transport as well as high-performance aircraft. Some of the recent flight experiences of pilot-in-the-loop with an adaptive controller have exhibited unpredicted interactions (Bosworth & Williams-Hayes, 2007; Page, Meloney, & Monaco, 2006). In retrospect, this is not surprising once it is realized that there are now two adaptive controllers interacting, the traditional software adaptive control system and the pilot. The pilot is another entity that may affect the attitude of the vehicle (definition of a control system), and the pilot's method of controlling may change due to slowly varying or uncertain system parameters. One hypothesized reason for the pilot-in-the-loop with an adaptive controller interactions is that it is due to the pilot not realizing what the adaptive controller is doing and what the limits of the adaptive controller are.

The experiment objectives were to determine (1) how the adaptation time of the controller affects pilots and (2) how pilots want information about the control authority (or maneuver capability) available to them transmitted.

Method

This experiment looked at whether an adaptive controller helps pilots during control surface failures and whether displays indicating how close the vehicle is to reaching the limit of safe maneuver envelope were helpful before, during, and after the control surface failures. The limits indicated to the subjects were bank angle, vertical velocity, and aircraft speed (Trujillo & Gregory, 2013; Wilborn, 2001). Furthermore, these variables were used in two displays designed to inform the pilot of available maneuverability envelope. These displays were then used in a human-in-the-loop experiment to look at their effects on pilot performance with aircraft surface failures during cruise phase while initiating a climb, descent, or a heading change maneuver. These maneuvers were indicated on the primary flight display (PFD) via the flight director.

Simulation Environment

The physical setup of the simulator incorporated an out-the-window view in the upper center 30-inch diagonal screen and four 20-inch touchscreens below the out-the-widow screen. The middle-left touchscreen depicted the PFD and the middle-right touchscreen depicted the engine indication display (EID). The far-left touchscreen contained the control authority display when present and the far-right touchscreen displayed the after run questions. Subjects flew the aircraft with a right-handed joystick.

Independent Variables

Display Type. The two displays tested were the dial display (Figure 1) and the circle display (Figure 2). In both displays, the information shown was the same but the format was different. In each display, a green wedge filled in from zero the percentage of available safe maneuver envelope used in the task. For example, for vertical velocity (VVel) in Figure 1, the aircraft is descending at 100% or more of available 3000 ft/min. When the available control authority changed from normal due to failure, the displayed number went from white to cyan in color and the limit value changed to the newly available one. For example, for minimum speed (Min Spd) in Figure 2, the aircraft's safe minimum speed is now 120 kts as indicated by the cyan number.

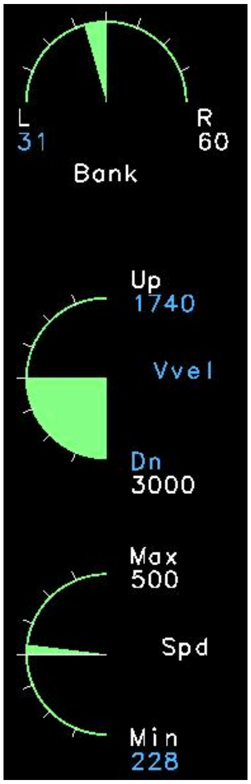

Figure 1. Dial Display

Adaptation Time. Each subject experienced four adaptation times: zero seconds, three seconds, seven seconds, and no adaptation (Never). These times indicated how long it took the adaptive controller to settle to new aircraft dynamics and are based on the response of aircraft dynamics. Zero seconds indicated the fastest possible adaptation time, essentially the processor speed. Three seconds was chosen because with this time, the subject might notice the controller adapting. As for seven seconds, this was chosen because the subject should notice the controller adapting.

Subjects. The seventeen subjects were an average of 48±10 years old with the youngest 29 years old and the oldest 61 years old. All of them were airline transport rated pilots with an average of 26±11 years of flight experience (minimum flight experience = 7 years and maximum flight experience = 45 years) and an average of 10,706±7164 hours of flight experience (minimum flight hours = 2,100 and maximum flight hours = 23,400).

Dependent Variables

The primary dependent variables involved flight technical data. In particular in the lateral axis was cross track error, the difference between current aircraft position and commanded position, and roll error, the difference between current bank angle and commanded bank angle. In the longitudinal axis was altitude error, the difference between current aircraft altitude and commanded altitude, and pitch error, the difference between current aircraft pitch angle and commanded pitch angle.

Two other secondary dependent variables involved subjective ratings by the participant. After each run, subjects provided a Cooper-Harper (CH) handling qualities (HQ) rating (Cooper & Harper, 1969; Harper & Cooper, 1986; Trujillo, 2009). After certain runs, subjects also gave a NASA-TLX workload rating (Hart & Staveland, 1988; Trujillo, 2011).

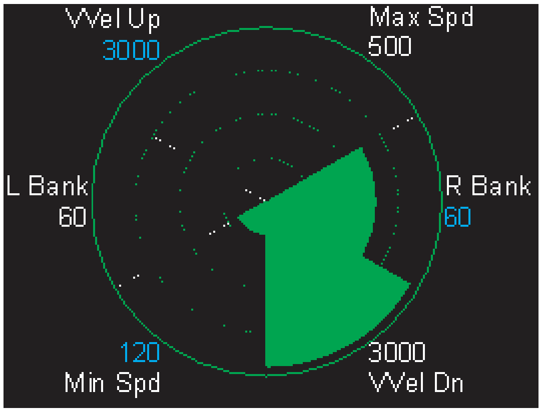

Figure 2. Circle Display

Procedure

Each subject had several runs without the new displays (None), then several runs with either the circle or dial display, and finally several runs with the other display. During each run, flight technical data were recorded. After each run, subjects gave a CH rating and a NASA-TLX workload rating. After all the data runs were completed, subjects filled out a final questionnaire asking them about their preferences on the information in the displays and displays themselves.

Results

Flight Technical Data

Lateral Error. Adaptation time was significant for cross track error during ($F_{(2,868)}$=36.90, p≤0.01) and immediately after ($F_{(2,873)}$=28.36, p≤0.01) the control surface failure and roll error was significant during ($F_{(2,868)}$=26.07, p≤0.01), immediately after ($F_{(2,873)}$=3.79, p≤0.03), and after ($F_{(3,1157)}$=7.54, p≤0.01) the control surface error. In general, the 3 sec adaptation time was associated with the least cross track error (Figure 3) and roll error (Figure 4). This may indicate that while subjects were able to follow the flight path with no adaptation, fine motion was compromised.

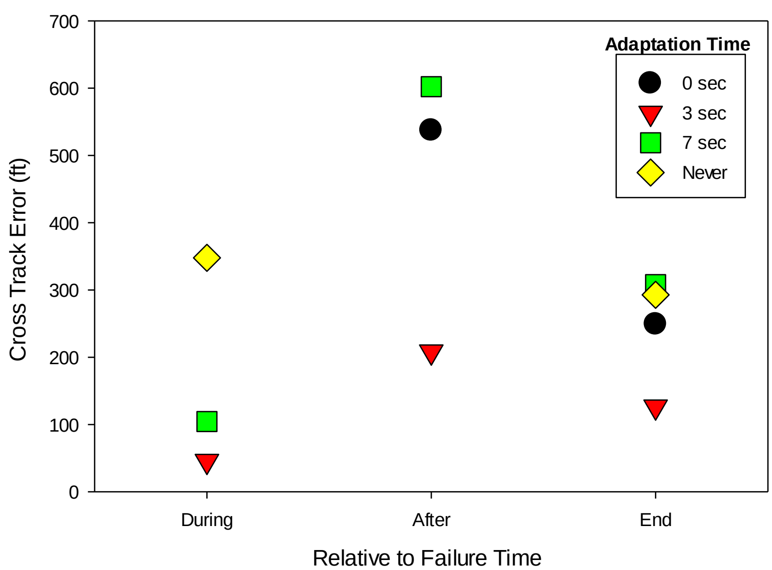

Figure 3. Cross Track Error During, Immediately After, and at the End by Adaptation Time

Unsurprisingly, when the adaptive controller never engaged, subjects improved their performance for both cross track error and roll error as time progressed. This suggests that indeed subjects were adapting to the vehicle's new dynamics. Also note that when the adaptive controller never engaged, the lateral errors were greater than with an adapting controller. In fact, the roll error with the adaptive controller was less than the roll error before the control surface failure. This indicates that the adaptive controller was helping the subjects control the aircraft and given enough time, the cross track error decreased.

Longitudinal Error. Adaptation time was significant for altitude error during ($F_{(2,868)}$=201.25, p≤0.01), immediately after ($F_{(2,873)}$=47.83, p≤0.01), and at the end of the run ($F_{(3,1157)}$=41.83, p≤0.01) and was significant for pitch immediately after ($F_{(2,873)}$=10.92, p≤0.01) and at the end ($F_{(3,1157)}$=12.73, p≤0.01) of the run. The zero and seven second adaptation times were associated with the least altitude error (Figure 5) and pitch error (Figure 6).

Again, as with lateral error, when the adaptive controller never adapted, subjects improved their

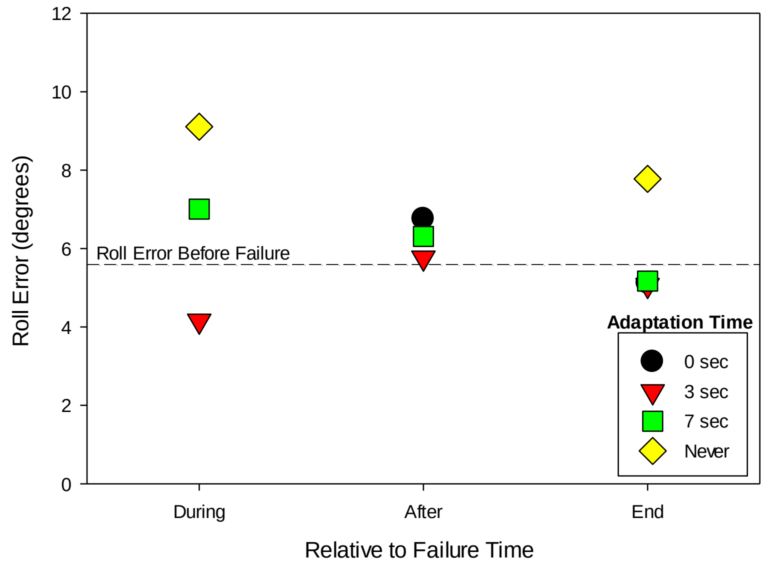

Figure 4. Roll Error During, Immediately After, and at the End by Adaptation Time

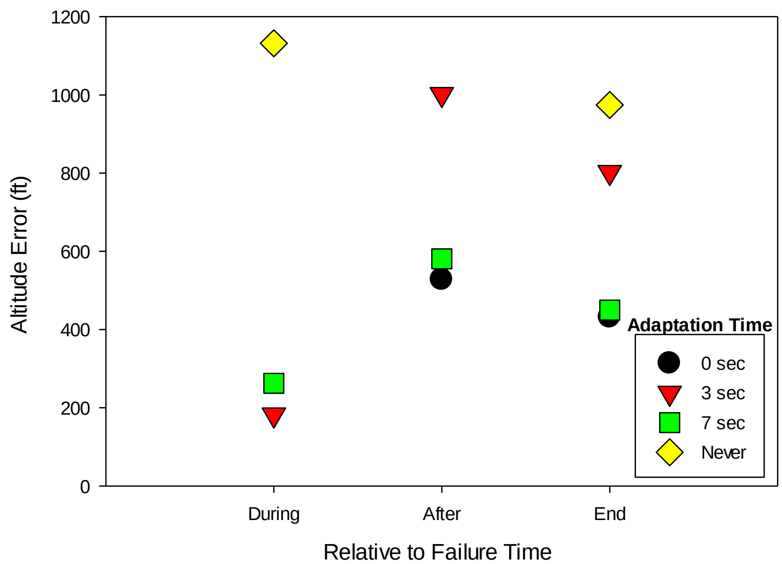

Figure 5. Altitude Error During, Immediately After, and at the End by Adaptation Time

performance for both altitude error and pitch error as time progressed. As before, when the adaptive controller never adapted, the longitudinal errors were greater than with an adapting controller.

Display type was significant for altitude error before the failure ($F_{(2,1175)}$=4.05, p≤0.02). As can be seen in Table 1, the least amount of altitude error is associated with no display. Although not significant, this trend also held for altitude error immediately after the failure and at the end. Without the display present, subjects were able to perhaps expend more attention on the PFD maintaining aircraft path.

Table 1.
Altitude Error Before the Failure by Display Type

Display Type	Altitude Error (ft)
None	42.98
Circle	56.80
Dial	59.77

Cooper-Harper Handling Qualities Ratings

Both display type (Figure 7) and adaptation time (Figure 8) were significant for the CH rating (display: $F_{(2,1157)}$=4.06, p≤0.02 ; $F_{(3,1157)}$=17.56, p≤0.01). With the new displays, the CH ratings increased slightly indicating poorer handling qualities. This decrease in HQ may be due to the subjects having to expend resources to process the new displays rather than focusing on maintaining aircraft control. The CH ratings improved with the adaptive controller. As seen with the flight technical data, the three second adaptation time appears to improve the CH ratings the most.

Workload

Adaptation time was significant for workload ($F_{(3,764)}$=5.29, p≤0.01). As can be seen in Table 2, no adaptation had a higher workload than the other three adaptation times. This suggests that the adaptive controller did decrease the workload of the subject during control surface failures.

As for display type, it was only significant for mental workload ($F_{(2,764)}$=3.51, p≤0.02). The two

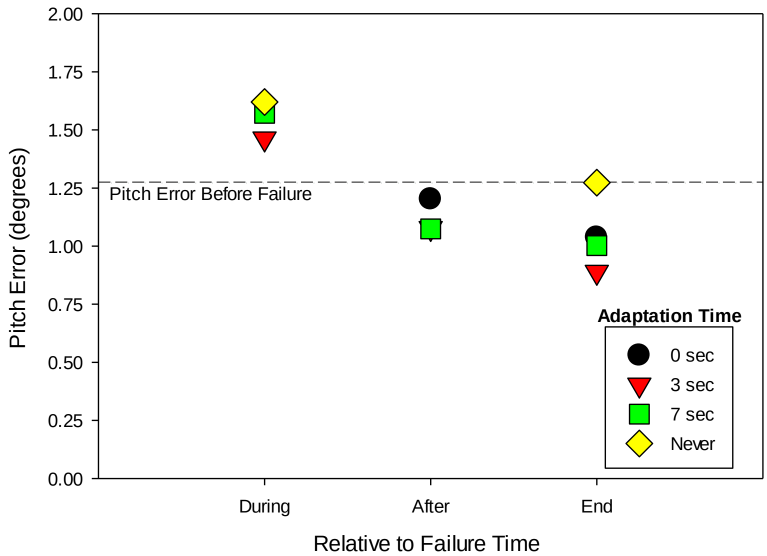

Figure 6. Pitch Error During, Immediately After, and at the End by Adaptation Time

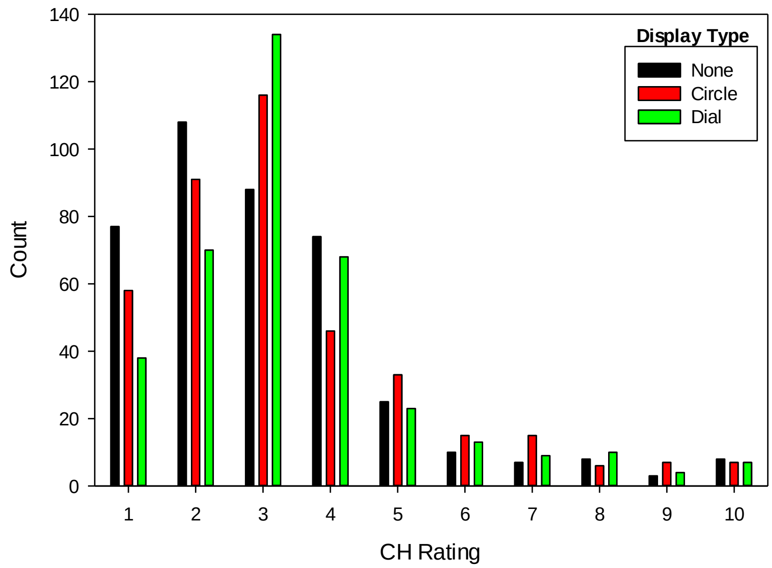

Figure 7. Frequency of CH Rating by Display Type

Table 2.
Select NASA-TLX Ratings by Adaptation Time and Display Type

Adaptation Time	**Workload**
0 sec	21.64
3 sec	24.42
7 sec	22.52
Never	35.29
Display Type	**Mental Demand**
None	23.32
Circle	29.04
Dial	25.99

Note. 0 = Low; 100 = high ratings.

displays did increase mental demand (Table 2) indicating that the displays did require some mental resources from the subjects. Of the two displays, the dial display required less of an increase in mental resources. This was most likely because the dial-type display was a familiar format to the subjects whereas the circle display was new to them and not used in current flight decks.

Conclusions

Adaptive control is beneficial for highly uncertain, and potentially unpredictable, flight dynamics that are characteristic of upset recovery or damage induced on transport or high-performance aircraft. But with an adaptive controller and a pilot, there are now two adaptive systems interacting, the traditional software adaptive control system and the pilot. The pilot controls the attitude of the vehicle (definition of a control system) and the method of control may change due to slowly varying or uncertain system parameters. This experiment looked at whether an adaptive controller helps pilots during control surface failures and whether displays indicating how close the vehicle is to reaching the limit of safe maneuver control authority were helpful before, during, and after the control surface failures. The limits indicated to the subjects were bank angle, vertical velocity, and aircraft speed.

Results indicate that an adaptive controller that takes three seconds to adapt helped the pilot most when looking at lateral and longitudinal errors. This adaptation time may be short enough to cause minimal interactions with the pilot possibly adapting but long enough to have the pilot realize that the aircraft has a control problem. Another possibility is the instantaneously adapting controller was too

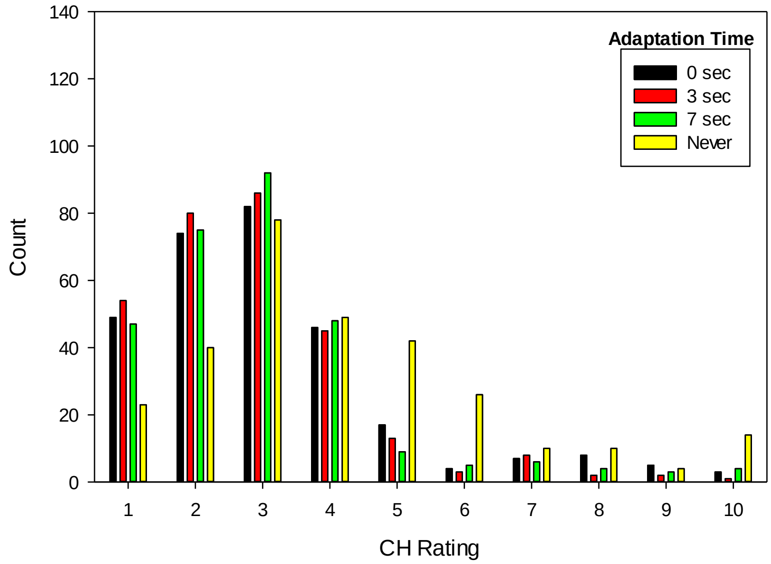

Figure 8. Frequency of CH Rating by Adaptation Time

sensitive for the pilots to fly comfortably. Handling quality ratings improved with the adaptive controller, again for the three second adaptation time, while workload decreased with the adaptive controller. The adaptive controller was helping the subjects control the aircraft and given enough time, subjects' lateral and longitudinal errors continued to decrease to be on par with errors before any control surface failures occurred. Even without an adaptive controller, subjects improved their performance by adapting to the vehicle's new dynamics.

The effects of the displays showing the percentage of available safe maneuver envelope used in the task were dominated by the adaptation time. With the displays, altitude error did increase along with a slight decrease in HQ. The additional display also required increased mental demand. Therefore, the displays did require some of the subjects' resources but these negative effects are minimal and may be outweighed by pilots having more situation awareness of a control problem with the aircraft and the failure's effects on their ability to control the aircraft.

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